Army Research Laboratory

Impact and Ballistic Response of Hybridized Thermoplastic Laminates

by Lionel Vargas-Gonzalez, Shawn M. Walsh, and James Wolbert

ARL-MR-0769 February 2011

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Aberdeen Proving Ground, MD 21005

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14. ABSTRACT
Recent Army research has focused on the use of thermoplastic-based polymer laminates for mass-efficient ballistic helmets. The focus of this work was to develop an understanding of how hybridization of ultra-high molecular weight polyethylene (UHMWPE) thermoplastic with various other thermoplastic and thermoset materials would affect ballistic performance and back face deformation. Panels of various material combinations and of varying architectures were processed and tested. Architecturally hybridized panels of UHMWPE exhibited the highest resistance to dynamic backface deformation. Generally, there were tradeoffs between ballistic performance and backface deformation within the variations of architecturally hybridized composites. However, several of the panels (the 50/50 and 90/10 hybrid series) exhibited projectile resistances comparable, and in a few cases superior, to that of the [0/90] plate while still exhibiting a higher level of deformation resistance.

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1. Introduction

Pursuit of mass-efficient materials and architecture for use in ballistic helmet technologies has been the focus of many U.S. Army Research Laboratory (ARL) projects in past research (*1–6*). Metals and ceramics are highly efficient ballistic materials, however, their relatively high penalty for weight compromises their usefulness in helmet technologies. Therefore, most of the researched ballistic helmet materials are in the area of lightweight polymer composites. Previously, the material of choice was lightweight Aramid. New manufacturing technologies and techniques have enabled the production of a ballistic helmet using thermoplastic ultra-high molecular weight polyethylene fibers, which exhibit the highest strength to weight ratios currently seen in any thermoplastic fiber material. However, one of the issues currently being faced by private manufacturers is the high deformation response of the backface in ballistic impact. The focus of this research is to determine if thermoplastic material can be improved through hybridization with other materials, or by clever use of architecture and orientation. Projectile and deformation response will be explored through experimental testing and innovative non-contact measurement methods.

2. Experimental

Commercially available thermoplastic and thermoset materials were processed into composite laminates. The baseline materials for the study were [0/90] laminates comprised of UHMWPE materials, specifically Spectra Shield II 3130 (Honeywell Specialty Materials, Morristown, NJ) and Dyneema HB25 (DSM, Geleen, The Netherlands). Hybridized panels consist of a skin or layer of a stiff thermoset or thermoplastic material on a Dyneema HB25 laminate. Multi-oriented panels or layers consist of HB25 laminates laid up in a quasi-isotropic fashion, with every two plies rotating clockwise 22.5°. Composite panels oriented in this manner are not necessarily symmetric; however, there were no issues with out of plane warpage or stress concentration. Care was taken to ensure that all of the panels had the same areal density (10.74 kg/m^2 or 2.2 lbs/ft^2); layers of HB25 were removed to accommodate the weight of the stiffening materials.

All sizes of laminate stacks tested for this work were consolidated and cured using a hydraulic press (Wabash 800 Ton Press, Wabash MPI, Wabash, IN) at 338 tons (20.8 MPa over part) and 125 °C for one hour. Hybrid laminates incorporating Tensylon (BAE Systems, Monroe, NC) were processed at a marginally lower temperature (115.5 °C) and 13.8 MPa pressure, as per manufacturer specifications.

Composite panels (0.38 m × 0.38 m) were tested ballistically with 9 mm, 124-grain FMJ rounds shot at a velocity of 473.13 ± 3.60 m/s. Backface deflection measurement was conducted using high-speed imaging. The maximum extent of dynamic deflection was measured in the high-speed camera acquisition software, with the optical length scale calibrated using a standard calibration scale. Panel deflections were taken from both an overhead and a side perspective to correct any aberration in optical methods of measurement.

After this initial testing, several composite panels were down selected, and a few observations led to the development of various hybridized [0/90] and multi-oriented panels. Panels (0.254 m × 0.254 m) were evaluated for dynamic and residual deformation using a laboratory gas gun and digital image correlation (DIC) collection methods. All panels were impacted with a 5.56 mm 440C steel ball bearing at a velocity of 405.7 ± 6.7 m/s. The velocity was kept as close to constant as possible through regulation of gas pressure in the charge. Velocities were measured through high-speed imaging and Doppler radar to ensure accuracy. Speckle patterns were applied to each test panel on the backface to enable the measurement of displacement and strain through DIC methods. Two Photron SA2 (Photron, USA) cameras mounted side by side create the ability to measure strain and displacement in the depth, as well as the length and width. All image analysis was performed using a commercially available image correlation package (Aramis, GOM mbH, Braunschweig, Germany).

Projectile impact testing was performed at the PEEP Site test range on Aberdeen Proving Ground. Panels (0.45 m× 0.45 m) were laminated and tested in this series. Each test was performed in an area of the panel where no existing delamination was present to avoid variability in testing. Delamination extent in the panel between tests was determined by the coin tap test and light table methods. Five panels were made for each orientation setup.

3. Results

The results of the initial testing to determine the extent of backface deformation resistance due to material hybridization are shown in table 1. Many different types of hybrid combinations have been evaluated, yet, few points can be made about the resistance to deformation from the data.

Table 1. Deflection data for hybridized laminates.

Panel Type	Velocity (f/s)	Overhead Deflection (mm)	Side Deflection (mm)	Comment
HB25 (multi-orientation)	1421.64	5.563	7.5946	
HB80 (multi-orientation)	1428.76	5.563	7.6454	
HB80 (multi-orientation) + 2-ply Carbon	1429.51	6.680	6.5532	Shot on Carbon Face
HB25 (multi-orientation)	1419.77	6.680	7.5946	
HB80 (multi-orientation) + 4-ply Carbon	1438.30	6.680	7.7216	Shot on Carbon Face

Table 1. Deflection Data for Hybridized Laminates (continued).

Panel Type	Velocity (f/s)	Overhead Deflection (mm)	Side Deflection (mm)	Comment
HB25 Mixed Panel 50% MO and 50% [0/90]	1424.33	7.036	6.6294	Shot on [0/90] Face
HB25 Mixed Panel 40% MO and 60% [0/90]	1445.16	8.052	6.6294	Shot on [0/90] Face
HB25 Mixed Panel 25% MO and 75% [0/90]	1415.57	9.042	7.7216	Shot on [0/90] Face
HB25 Mixed Panel 10% MO and 90% [0/90]	1419.86	13.081	12.1412	Shot on [0/90] Face
50/50 Mix HB25/Tensylon II	1431.64	13.360	13.0556	Shot on HB25 Face
75/25 Mix HB25/Tensylon II	1426.95	13.360	15.2146	Shot on Tensylon Face
50/50 Mix HB25/Tensylon II	1432.00	13.564	13.0556	Shot on Tensylon Face
HB25 + 4-ply Carbon	1430.92	14.402	12.9794	Shot on HB25 Face
HB25 + 2-ply Carbon	1426.23	14.402	15.1384	Shot on HB25 Face
60/40 Mix HB25/Tensylon IV	1444.37	14.478	15.2146	Shot on HB25 Face
HB25 Mixed Panel 50% MO and 50% [0/90]	1450.38	15.088	15.4686	Shot on Multi-orientation Face
HB80 + 2-ply Carbon	1451.82	15.596	14.7066	Shot on Carbon Face
75/25 Mix HB25/Tensylon II	1428.26	15.596	15.1892	Shot on HB25 Face
HB80 + 705/CS800/Mark III (Stitched Cross 10 ply)	1437.61	15.596	15.2146	Shot on Stitched Face
HB80 + 705/CS800/Mark III (Stitched Hatch 10 ply)	1430.36	15.596	16.3068	Shot on Stitched Face
HB25 Mixed Panel 10% MO and 90% [0/90]	1438.60	15.596	17.4752	Shot on Multi-orientation Face
HB25 + 2 Layer K705 Phenolic	1422.00	15.646	15.1638	Shot on Aramid Face
60/40 Mix HB25/LF1	1424.06	15.646	16.256	Shot on HB25 Face
Dyneema HB80	1451.82	16.688	16.3068	
90/10 Mix HB25/Tensylon IV	1428.00	16.688	18.4658	Shot on HB25 Face
HB25 + 4-ply Carbon	1450.00	16.688	18.4658	Shot on Carbon Face
50/50 Mix HB25/Tensylon IV	1445.00	16.688	19.558	Shot on Tensylon Face
HB25 + 2-ply LF1	1418.22	16.713	17.3482	Shot on LF1 Face
60/40 Mix HB25/Tensylon IV	1446.24	16.713	17.78	Shot on Tensylon Face
60/40 Mix HB25/LF1	1435.55	16.739	16.256	Shot on LF1 Face
2.2 PSF HB25 + 2 Layer GS + 2-ply Carbon	1420.46	16.764	16.3576	Shot on Carbon Face
HB25 + 3-ply LF1	1427.38	16.866	18.4404	Shot on LF1 Face
HB25 + 2 Layer K745 Phenolic	1418.00	16.891	16.2052	Shot on Aramid Face
Dyneema HB25	1430.00	17.120	16.3068	
HB25 + 2 Layer GS	1453.00	17.145	17.4498	Shot on HB25 Face
HB25 + 4 Layer GS	1446.83	17.145	18.542	Shot on HB25 Face
HB25 Mixed Panel 40% MO and 60% [0/90]	1438.60	17.475	15.5956	Shot on Multi-orientation Face
HB25 + 2 Layer GS + 2-ply Carbon	1434.76	17.729	16.2052	Shot on Carbon Face
2.2 PSF HB25 + 2-ply Carbon	1412.65	17.729	16.256	Shot on Carbon Face
Tensylon IV	1420.00	17.729	18.3642	
90/10 Mix HB25/Tensylon IV	1457.00	17.805	19.558	Shot on HB25 Face

Table 1. Deflection Data for Hybridized Laminates (continued).

Panel Type	Velocity (f/s)	Overhead Deflection (mm)	Side Deflection (mm)	Comment
50/50 Mix HB25/Tensylon IV	1435.00	17.805	20.6502	Shot on Tensylon Face
HB25 + 705/CS800/Mark III	1452.00	17.805	20.6502	Shot on Aramid Face
HB25 + 6 Layer 707	1458.00	17.805	20.6502	Shot on Aramid Face
90/10 Mix HB25/Tensylon II	1425.31	17.831	18.4404	Shot on Tensylon Face
HB25 + 4-ply LF1	1431.91	17.831	18.4404	Shot on LF1 Face
HB25 Mixed Panel 25% MO and 75% [0/90]	1438.43	17.831	18.542	Shot on Multi-orientation Face
90/10 Mix HB25/Tensylon IV	1450.00	17.856	18.4658	Shot on HB25 Face
90/10 Mix HB25/Tensylon II	1437.65	17.856	19.5326	Shot on HB25 Face
2.2 PSF HB25 + 2 Layer GS	1457.56	18.872	17.3228	Shot on Goldshield Face
90/10 Mix HB25/Tensylon IV	1439.00	18.923	20.6502	Shot on Tensylon Face
Spectra SSII 3130	1421.00	26.264	26.0858	

There is a large difference in deformation resistance between the various materials in the UHMWPE composite materials envelope. Spectra Shield II 3130 had the lowest deformation resistance of all samples. SSII 3130 exhibited a 53.4% higher deformation than the HB25 material, 26.264 mm versus 17.120 mm, respectively. A negligible difference of 2.5% in the deformation performance is observed between the two Dyneema materials (HB25 and HB80). Therefore HB25 was used for the testing, as more was readily available.

Several of the hybrids were tested with the stiffer skin facing outward toward the strike face and inward toward the interior. Most of the hybrid combinations shot with the stiffer skin inward toward the interior performed better than the same skin with the skin on the strike face. For example, the HB25 + IM7 Carbon skin composite performed marginally better against deformation when shot with the carbon inward (14.402 mm vs. 16.688 mm for the HB25 + 4-ply carbon samples).

Although many materials and hybrid combinations of materials were evaluated, there was no indication that hybridized samples were making a substantial improvement in the deformation performance. The next effort was to determine the effectiveness of using quasi-isotropic orientation in whole panels, and as layers in [0/90] panels. While previous work suggested that any orientation variance would yield lower penetration resistance, there was no evidence as to how much these properties would deteriorate. In the 9 mm deformation testing, the multi-oriented panel performances were vastly superior to the [0/90] composite panels. [0/90] HB25 exhibited a 125% higher deformation than that of the fully multi-oriented HB25 panel. Hybridized panels comprised of varying percentages of [0/90]/multi-oriented layers also generally performed better than the [0/90] composite panels. Panels with ratios of 10-50% multi-oriented content, which were ballistically excited on the multi-oriented side, were in the general spectrum of the [0/90] panel performance regime; generally speaking, those with higher

(40–50%) multi-oriented content were on par or marginally better than the [0/90] panels, and those under 40% were worse. Hybridized panels shot on the [0/90] side had low deformation values, however, it was assumed that these panels would not perform well in the penetration testing (as compared to the [0/90] composite panels).

These test results led to the abandonment of further testing of thermoplastic/thermoset hybrid panels, and continuation of projectile testing on the hybridized multi-orientation/[0/90] panels. HB25 [0/90] and 50/50 hybrid multi-orientation/[0/90] composites were chosen for further analysis. Furthermore, a 25/50/25 hybridized panel was added to this test, where the total material count by weight would still be 50% multi-oriented and 50% [0/90], however, the material would be split to make a front and back face "skin" on these panels. For one set, 50% of the interior of the panel was [0/90], while the outside 25% of the panel on each face was multi-oriented. The other set had the reverse configuration. An aramid panel (K705) with a thermoset resin was also added in this test for a reference baseline.

Table 2 shows the results obtained from the gas gun deformation testing, which uses image correlation (DIC) to provide non-contact 3-dimensional displacement and strain measurement. The max deflection is the maximum extent of out of plane displacement (in the z-direction) during the ballistic event, which occurs immediately after impact (less than 0.2 ms). The residual deflection is measured after the panel has reached an equilibrium deformation extent. Figure 1 illustrates the numbers graphically for each panel test. At this threat and velocity, Aramid and [0/90] HB25 perform similarly, with the Aramid panel having the slight advantage in deformation resistance. Going to a monolithic multi-oriented panel reduces the dynamic maximum deflection over [0/90] by ~32%. In the 50/50 mixed hybrid samples, the panels tested, using the [0/90] layer as the strike face, exhibited a lower deflection than the same panel being tested on the multi-orientation strike face. This behavior was also evident in the 25/50/25 panel; the panel with the [0/90] outer faces exhibited a lower deflection than the reverse layup. Figure 2 shows the deflection in real time over the first millisecond following the impact of the panel with the threat. This information gives an indication into how the material behaves during impact. Interestingly, all HB25 composite panels have the same sinusoidal behavior and frequency, even with differences in the architecture of the panels. The Aramid panel has its own distinct frequency of energy dissipation.

Table 2. Deflection data from DIC testing for hybrid laminates.

Sample	**Max Deflection (mm)**	**Residual Deflection (mm)**
K705 Aramid (Phenolic)	3.156	1.284
[0/90]	3.303	1.486
Multi-oriented	2.255	1.139
50/50 Hybrid (Multi-oriented Strikeface)	2.522	1.175
50/50 Hybrid ([0/90] Strikeface)	2.120	1.079
25/50/25 Hybrid (Multi-oriented Faces)	2.342	1.163
25/50/25 Hybrid ([0/90] Faces)	2.090	0.847

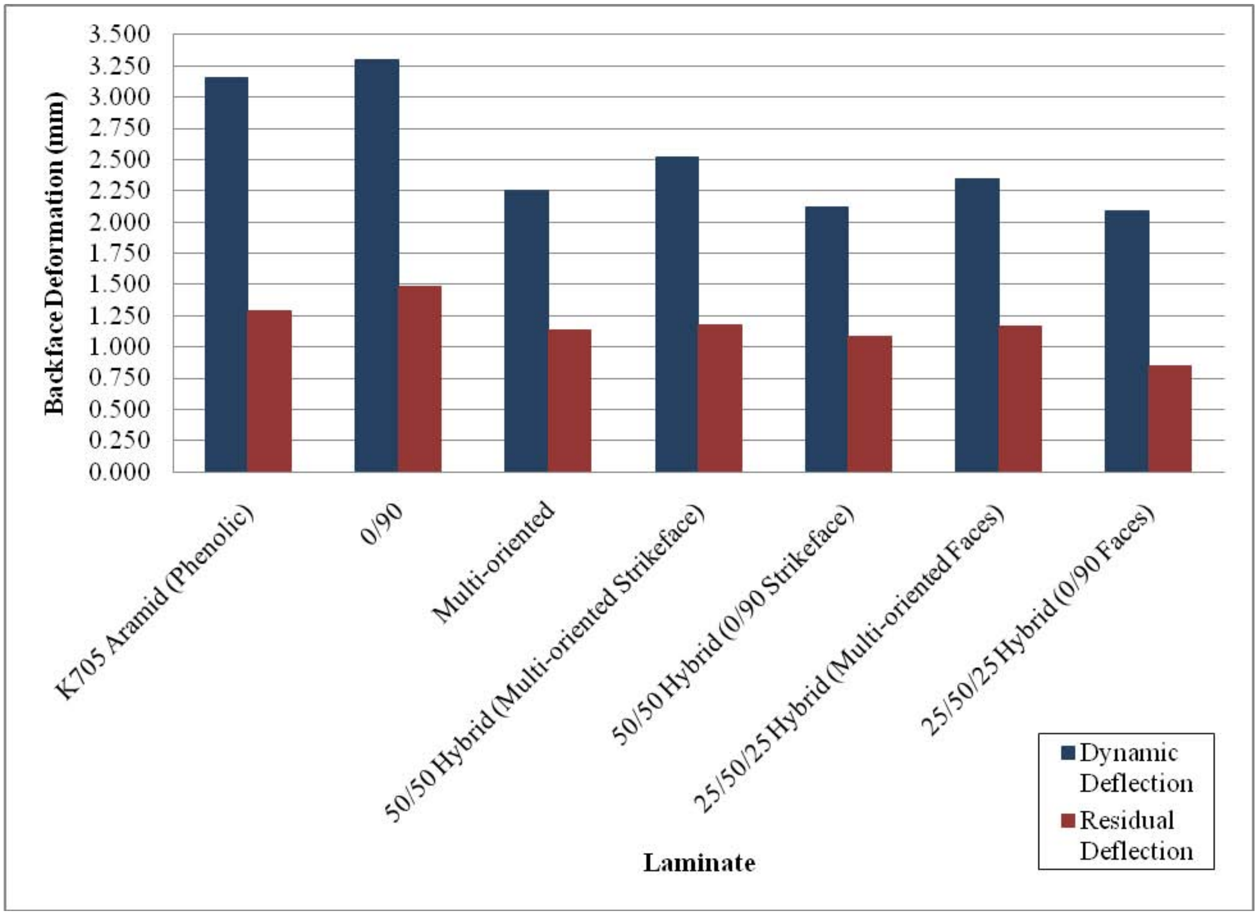

Figure 1. Deformation data for hybrid laminates as measured through DIC method following gas gun impact (.22 cal FSP ball, 405.7 ± 6.7 m/s). The hybrid panels exhibit the lowest dynamic and residual deflection through all samples. Kevlar and [0/90] HB25 layup are similar in performance.

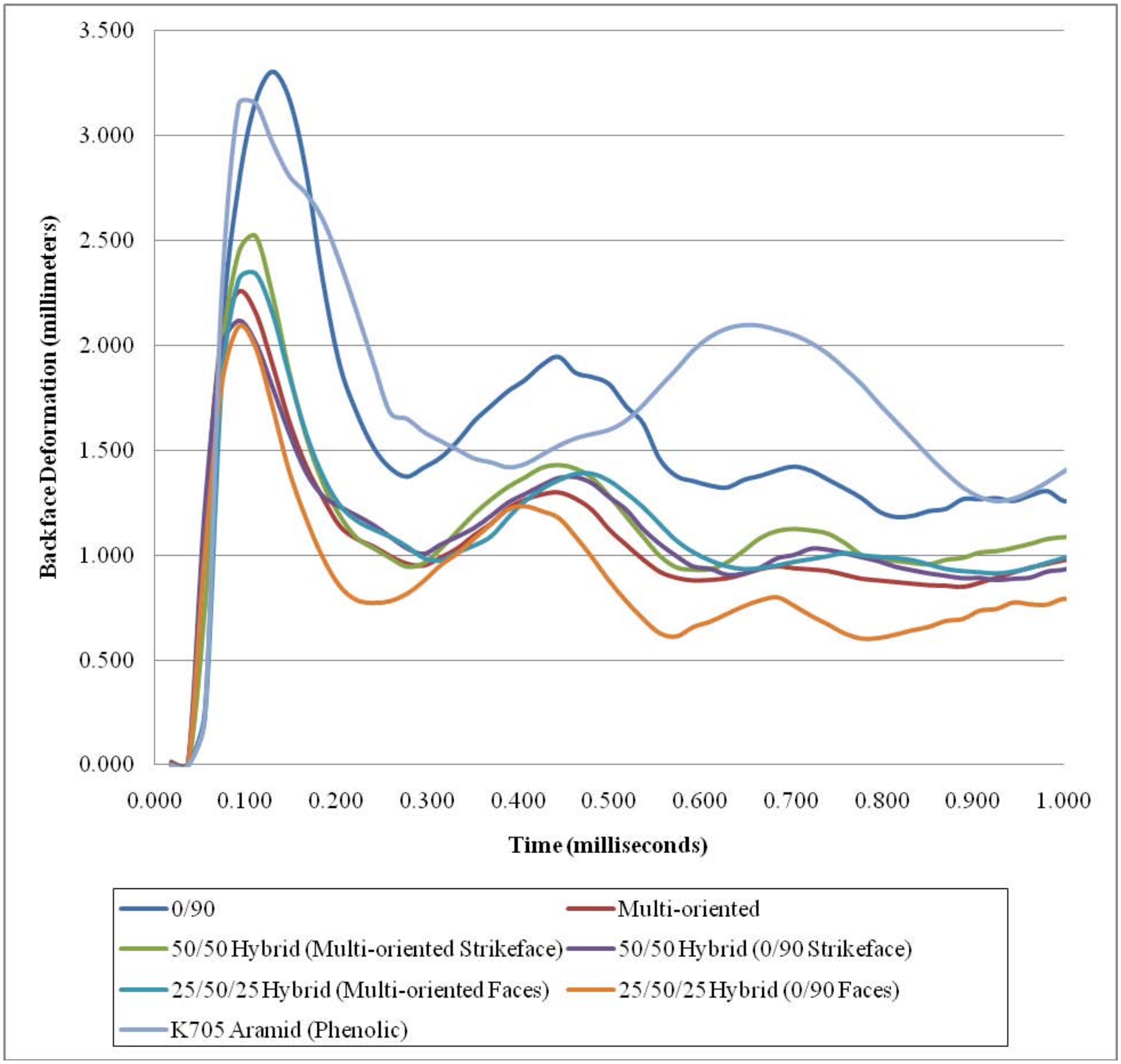

Figure 2. Material response through the first millisecond following gas gun impact (.22 cal FSP ball, 405.7 ± 6.7 m/s). All HB25 laminates exhibit similar frequency characteristics, regardless of layup design. The aramid panel exhibits a unique characteristic frequency.

Illustrations of how the displacement wave is distributed on the panels during the instantaneous time marking the maximum extent of deflection is shown in figure 3. As shown with the graphs and numbers in the previous tables and figures, Aramid and [0/90] HB25 panels exhibited the highest dynamic deflection extent. These images reveal the pattern of deformation exhibited in each panel, which gives an indication of how the panel is strained. In the hybrid laminate panels where the [0/90] component is on the backface, it is observed that the cardinal directions are being loaded the most, which shows that the load is primarily transferred down the fiber direction (0° and 90°). The multi-oriented panel, and the panels with multi-oriented outers and

backfaces, show a more circular and further diameter of panel involvement. The load is transferred to fibers in all directions, which eventually spreads to involve the entire panel, as is evident in the high-speed videos of the impacts.

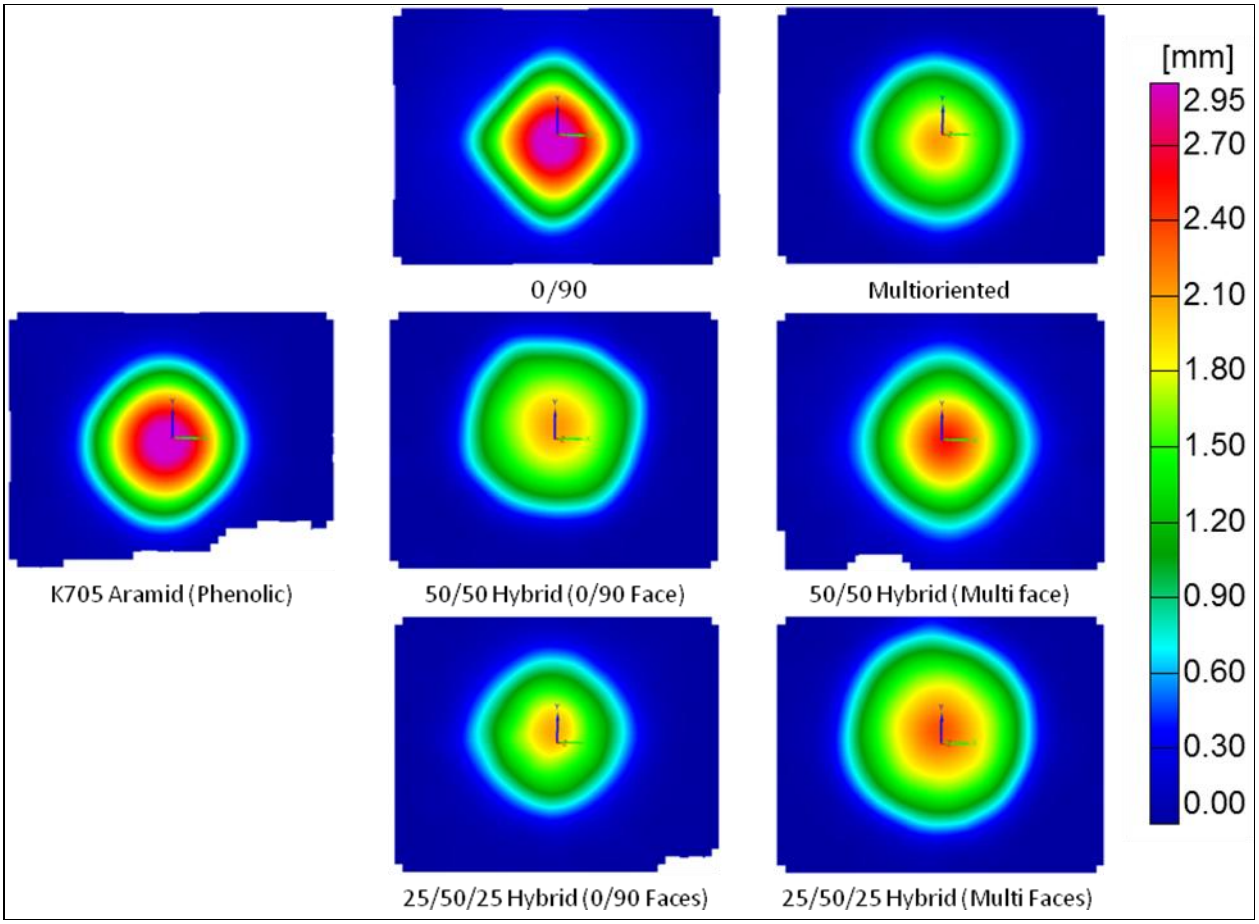

Figure 3. DIC images showing the maximum extent of deformation in hybrid samples hit with the gas gun projectile. The material behavior can be seen clearly through the shape of the strain field exhibited on the DIC analysis.

The projectile resistance data for all the HB25 hybrid panels are in the initial round are listed in table 3, and illustrated graphically in figure 4. For this test, three backface deformation tests were conducted with a 9 mm on each panel to obtain a more representative spread of values. These tests were done on the 0.145 m^2 panels, again with one shot per panel placed at the center. The projectile impact tests were performed on the 0.20 m^2 panels. Each panel was impacted as many times as could be managed without overlapping delaminated areas from previous tests. Following the initial testing, we made a second set of panels to explore 90/10, 75/25, and 60/40 hybrid variations. The results for these test panels are listed in table 4 and included in figure 4.

Table 3. Performance data for HB25 hybrid panels.

Type	BFD (mm)	Average BFD (mm)	St. Dev BFD (mm)	Measure of Resistance to Projectile Impact (norm)	St. Dev. Impact Testing
Multi-oriented	8.280 8.128 8.280 5.563	7.563	1.335	0.789	0.060
50/50 Hybrid ([0/90] Face)	7.036 6.502 9.754 9.754	8.261	1.737	0.847	0.00
50/50 Hybrid (MO Face)	15.088 16.332 14.630 17.958	16.002	1.489	1.025	0.034
[0/90]	17.120 19.583 17.958 19.507	18.542	1.208	1.000	0.029
25/50/25 Hybrid (MO Face)	17.577 11.379 13.005	13.987	3.213	0.888	0.004
25/50/25 Hybrid ([0/90] Face)	9.322 8.128 9.754	9.068	0.842	0.887	0.007

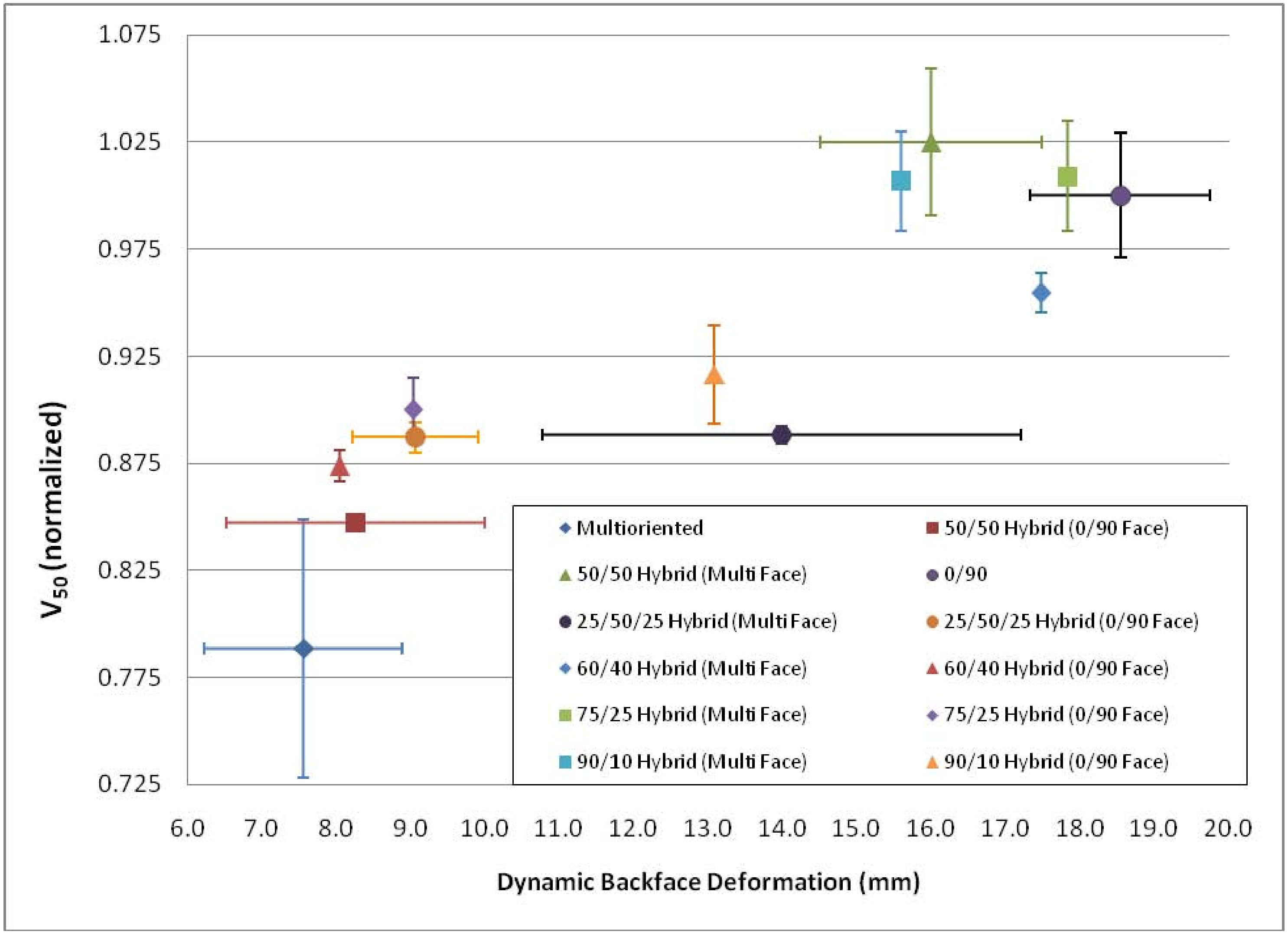

Figure 4. Ballistic performance plotted as a function of dynamic backface deformation (using 9 mm, 473.1 ± 3.6 m/s). As surmised, the stiffened panels generally exhibited lower projectile resistance values as the orientation percentage increased.

Table 4. Second round of performance data for HB25 hybrid panels.

Type	BFD (mm)	Measure of Resistance to Projectile Impact (norm)	St. Dev. Impact Testing
60/40 Hybrid (MO Face)	17.475	0.955	0.009
60/40 Hybrid ([0/90] Face)	7.036	0.874	0.007
75/25 Hybrid (MO Face)	17.831	1.009	0.026
75/25 Hybrid ([0/90] Face)	9.042	0.900	0.014
90/10 Hybrid (MO Face)	15.596	1.007	0.023
90/10 Hybrid ([0/90] Face)	13.081	0.916	0.023

The results prove that the multi-orientation layup of the polyethylene material has a deleterious effect to the penetration resistance. The penetration resistance of the multi-oriented panel is 21.1% lower than that of the [0/90] panel. There was no change in the penetration resistance between the 25/50/25 samples when shot on either side, however, the deformation between them varied widely, even within panels in the same series. The delamination was widespread and highly irregular (figure 5) versus the small, repeatable delamination exhibited in the [0/90] panel, which led to the high standard deviation in backface deformation of the 25/50/25 (Multi Face) hybrid sample. The large delamination in the mixed hybrid panels also had an impact on the repeatability of projectile testing. Because of the large delamination extent in these panels, it was difficult to obtain more than 5–6 test on each panel, making it difficult to obtain the threshold merit factor. The effects of the phenomena are shown in figure 6. The behavior of the [0/90] panel was more predictable, and had a smaller area of delamination behind each shot, making it easier to place more shots on each panel. For the 25/50/25 hybrids, three to four tests per panel were all that would fit in the panel without encroaching on previous delamination, which appreciably could affect the merit testing. However, since the merit value was based on tests on more than one panel, it is safe to assume that these merit factors are within an acceptable error. The result for the 50/50 (Multi Face) hybrid panel was surprising, as it exhibited a slightly lower backface deformation yet also had the highest projectile resistance (2.5% higher than [0/90]). The second round of tests, which included the 60/40, 75/25, and 90/10 hybrids were performed based on the surprising 50/50 hybrid results. These orientation and architecture

variations did not yield any higher penetration resistance than the 50/50 (Multi Face) hybrid. However, these panels yield varying compromise between backface deformation and penetration resistance, depending on the layup and the strike side. In general, the results prove that there is a tradeoff between stiffness and penetration resistance. However, this information is advantageous because it gives the end user high versatility for selecting a hybrid variant that will give the ideal mechanical behavior necessary for the intended application.

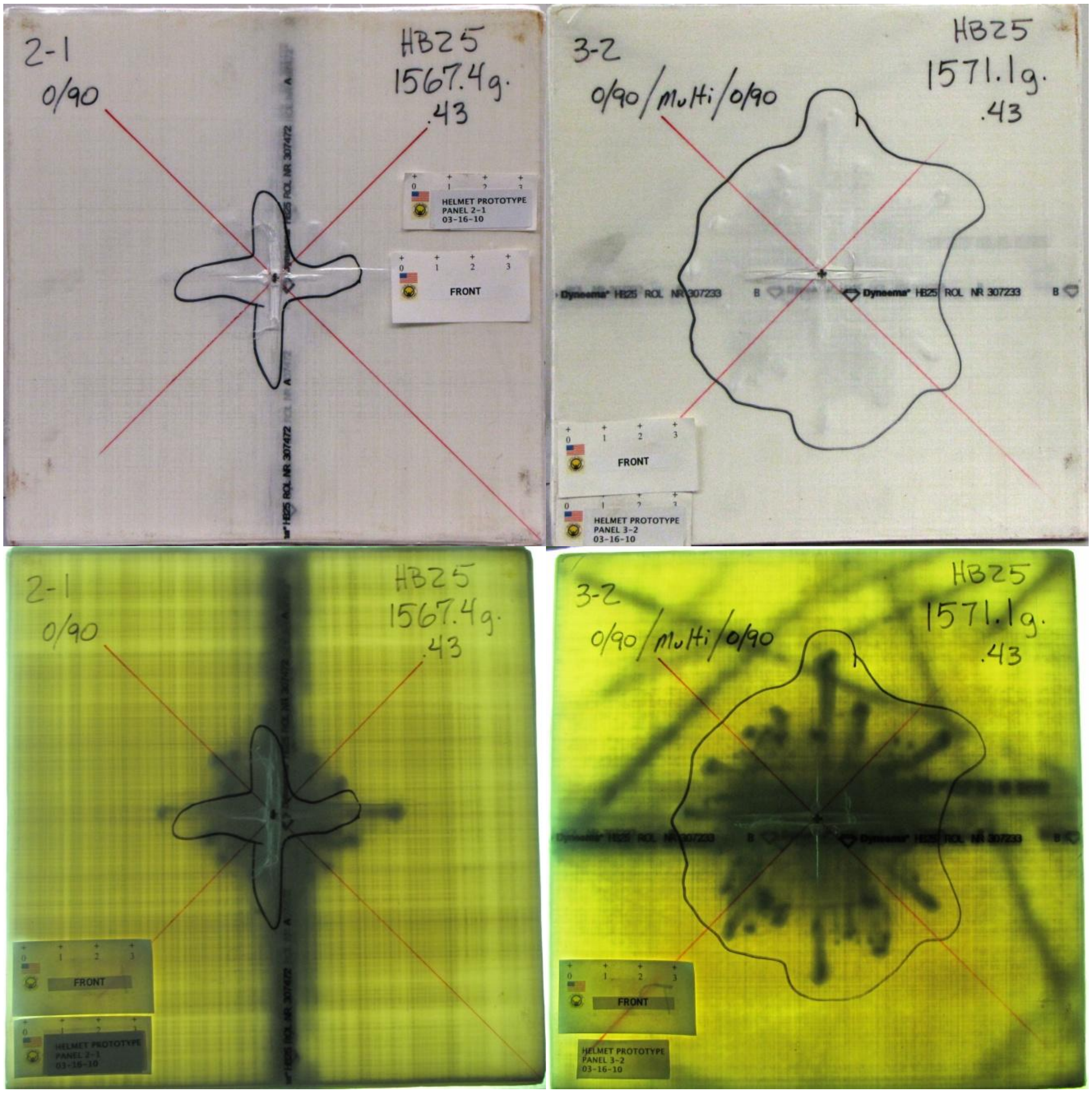

Figure 5. Variation in interlaminar delamination extent shown between samples of [0/90] and mixed hybrid laminates. The black borders measuring the extent of delamination were determined with the coin test method prior to light table imaging. Panel sizes are 0.38 m × 0.38.

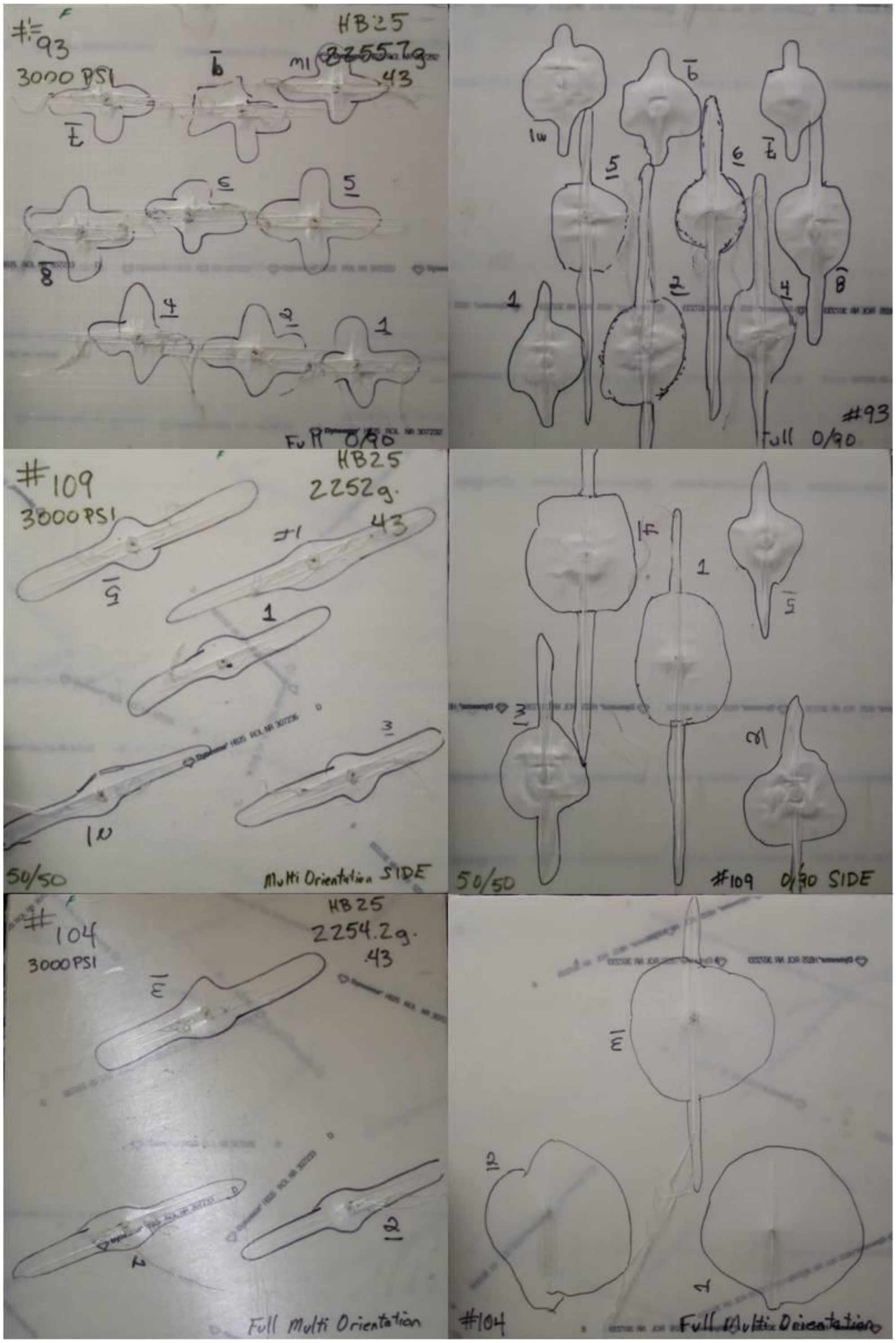

Figure 6. Projectile impacts on various hybridized panels. The panels with orientation variance and multilayer design show higher delamination extent, which made it difficult to obtain multiple tests for merit factor determination. Panel sizes are 0.45 m × 0.45 m.

The ultimate goal is for these new materials and hybrids to manifest themselves into new head protection systems that enable either the same level of protection at lighter weight or helmets with significantly high protection as the same current helmet weight. Thermoplastic matrices, together with both aramid and UHMPWE fibers, have tremendous potential, but they carry some complexities that must be addressed if these materials are to be used successfully in new helmet applications. The key complexities are the relative soft structural response of these materials, making both static and dynamic deformations a potentially limiting criterion in certain applications. Our present work explores in more detail the relationship between back face deformation and materials response (including monolithic, hybridized, and alternative fiber orientations) and to then correlate this with the influence on ballistic response. The goal is to develop sufficient understanding to enable the most robust and optimal use of these materials. Consistent with previous efforts, it is likely that meeting all helmet criteria simultaneously will require innovations at multiple levels, including materials selection, fiber types, resin types, bonding, hybridization, and micro and macro stiffening concepts (to include skins, chassis, and other novel stiffening design elements and approaches). Figure 7 summarizes some of the possible combinations to enable new performance levels that address both ballistic and structural requirements.

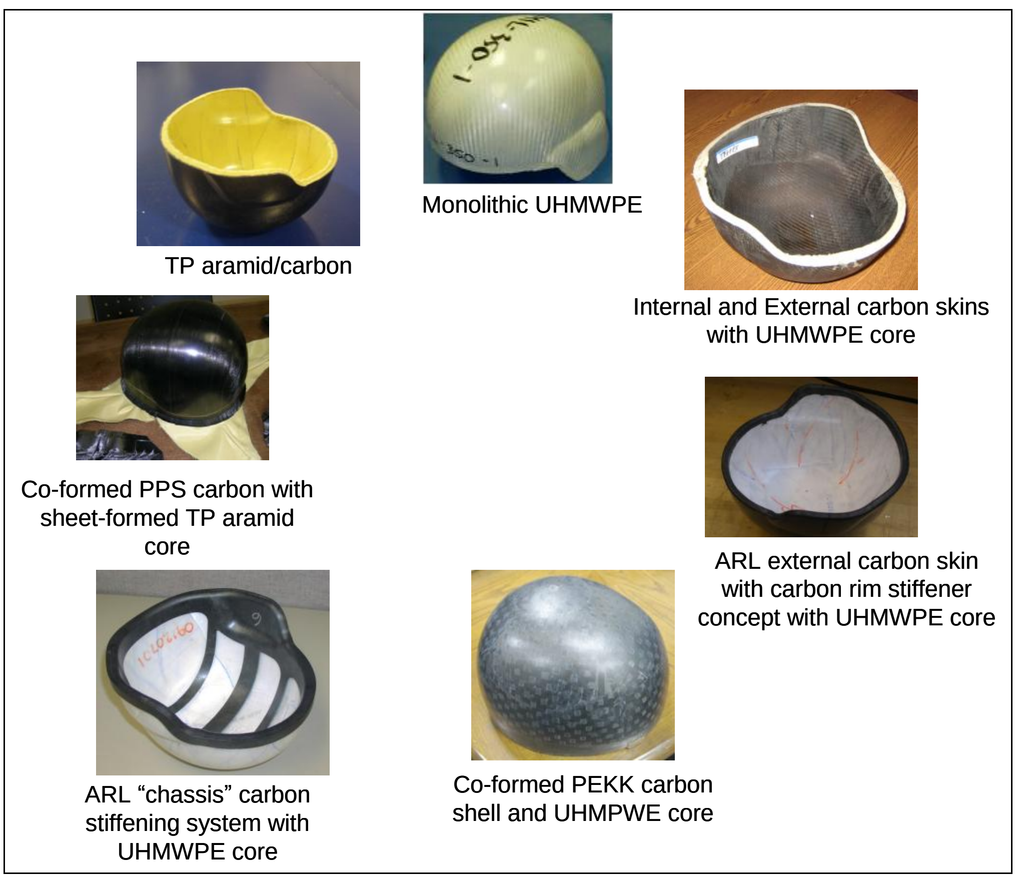

Figure 7. Concept methods for simultaneously enabling both ballistic and structural performance in weight-efficient helmet configurations.

4. Conclusion

The goals of this work were to develop a database of knowledge in order to discern how material hybridization and architecture affect ballistic and impact response. Thermoplastic and thermoset polymer composite materials were hybridized into laminates and impacted to determine projectile resistance and backface deformation. Material-hybridized panels did not meet the goals of large reduction in backface deformation. Structurally hybridized panels, made from ultrahigh molecular weight polyethylene materials, exhibited the most improvement in resistance to dynamic and residual deformation. The deformation response of the panel varied from the least deformation, with the fully quasi-isotropic panel, to the most deformation, with the [0/90] panel. All the rest of the hybridized panels exhibited varying levels of deformation response and projectile resistance within those two extremes. Several of the panels (the 50/50 and 90/10 hybrid series) exhibited projectile resistances comparable, and in a few cases superior, to that of the [0/90] plate. This, combined with the higher level of deformation resistance, makes the 50/50 and 90/10 hybrid samples ideal candidates for further evaluation.

Future objectives include continuing to explore other structurally hybridized panels in order to find other optimal hybrid combinations. Transitioning these architectures into useful geometries, such as ballistic helmets, will also be pursued and evaluated to determine the effect of shape on ballistic behavior. The influence of hydroclaving and other high uniform pressure processes on bulk performance properties is currently underway, and will build on the material characterization work of this report.

5. References

1. Riewald, P. G.; Folgar, F.; Yang, H. H.; Shaughnessy, W. F. Lightweight Helmet from a New Aramid Fiber. *Proc. 23rd SAMPE Tech. Conf.*, N.Y. 1991.

2. Walsh, S. M.; Scott, B. R.; Spagnuolo, D. M.; Wolbert, J. Examination of Thermoplastic Materials for Use in Ballistic Applications. *Society for Manufacturing Processing Engineering International Symposium*, May 2007.

3. Walsh, S. M.; Scott, B.; Spagnuolo, D. *The Development of a Hybrid Thermoplastic Ballistic Material with Application to Helmets*; ARL-TR-3700; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, December 2005.

4. Walsh, S. M.; Scott, B.; Spagnuolo, D.; Wolbert, J. Composite Helmet Fabrication Using Semi-Deformable Tooling. *Society for Manufacturing Processing Engineering International Symposium*, May 2006.

5. Walsh, S. M.; Spagnuolo, D. M.; Scott, B. R. The Potential Advantages of Thermoplastic and Hybridized Ballistic Materials and Processes for U.S. Army Helmet Development. *SAMPE Proceedings*, Long Beach, CA, May 2006.

6. Walsh, S. M.; Scott, B. R.; Spagnuolo, D. M. The Development of Hybridized Thermoplastic-Based Structural Materials with Applications to Ballistic Helmets. *Proceeding of the International Ballistics Symposium*, Vancouver B.C., November 2005.

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